Appendix XI

The Impact of Climate Change on Energy Expenditures in California

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Abstract

In this appendix, we use a national cross-sectional analysis and detailed data from California to examine the sensitivity of energy expenditures to climate change in the state. The analysis begins with a logit regression that explains the probability that a building will be cooled. Long- and short-run cross-sectional approaches are then explored to estimate the sensitivity of energy expenditures and buildings to changes in climate. The national analysis suggests that energy expenditures for both residential and commercial property have a U-shaped relationship with respect to temperature. This empirical relationship is then used to analyze climate change in individual counties in California. The results suggest that warming will increase average energy expenditures in residential and commercial buildings and cause damages, but the effects across the state are not uniform. Northern and mountainous counties are more likely to reduce energy expenditures (a benefit) and central valley and southern counties are more likely to increase energy expenditures (a damage). With mild climate scenarios, statewide annual projected damages are in the range of $1 billion to $9 billion but with more severe climate scenarios, damages can climb to between $8 billion and $18 billion by 2100.

1. Introduction

The energy sector plays a dual role in the climate change debate — it generates greenhouse gases that lead to climate change and it is affected when climate actually does change. This work measures the expected impact of climate change on energy demand. In an alternative analysis of the water system, other investigators for this project explored the effect of climate change on hydroelectricity production (Attachment A of Appendix VII). Here, however, we focus only on how climate change may affect energy consumption.

Four methods have been used to estimate climate impacts and reported in the literature:

- expert opinion (Nordhaus, 1991; Cline, 1992)
- engineering models (Baxter and Calandri, 1992; Rosenthal et al., 1995)
- case studies (Nelson, 1976; Linder et al., 1989; Smith and Tirpak, 1989)
- cross-sectional empirical studies (Crocker, 1976; Nelson, 1976; Belzer et al., 1996; Morrison and Mendelsohn, 1999).

All the approaches suggest that the relationship between energy demand and temperature should be U-shaped — very cool temperatures lead to high heating costs and very warm temperatures lead to high cooling costs. The different methods, however, do not always yield identical results. The engineering studies, for example, argue that the temperature that minimizes energy expenditures for commercial properties should be cooler than the cost-minimizing temperature for residential buildings. Commercial buildings have, for example, more lights that generate excess heat, so their costs should be lower in cooler environments. However, cross-sectional results reveal that , the residential buildings minimize energy costs. in cooler regions. In practice, homeowners in cooler places do not install cooling capacity (central air-conditioning), leading to lower energy costs than residents will see in warmer locations. The cross-sectional approach incorporates human behavior that changes the results. In this appendix, we rely on the cross-sectional method to estimate how climate might affect California energy demand.

The demand for energy derives from the demand for many residential and commercial services including lighting, hot water, refrigeration, and appliance use. However, the part of the energy sector that is most sensitive to climate change is space conditioning (heating and cooling). This is a large part of the U.S. residential energy sector, amounting to 36% of electricity demand and 70% of natural gas demand in 1990 (Energy Information Administration [EIA], 1992). Even in the Pacific region (California, Oregon, and Washington), space conditioning is an important component of residential energy use. In 1990, heating accounted for 24% of residential demand, and cooling represented another 6% of Pacific energy demand (EIA, 1992). Climate warming is expected to increase the cost of cooling and decrease the cost of heating by altering expenditures on energy and building structures necessary to maintain desirable interior temperatures. We review the theoretical basis of this work in Section 2.

In Section 3, we use data from across the United States to estimate an empirical model explaining how the energy sector adapts to climate. The model was estimated using residential and commercial buildings separately. The estimation relies on the entire country to achieve sufficient variation in climates. The analysis begins with a logit regression explaining the likelihood that a building is cooled. The expenditures on energy are then predicted by two additional regressions: a short-run and a long-run analysis.

The short-run model includes many building characteristics that are effectively held the same in the regression. By holding building characteristics constant, the short-run estimates look more like the engineering studies. The long-run approach allows climate-sensitive building characteristics to change with climate by estimating which building characteristics change with climate and then allowing these climate-sensitive building characteristics to adjust endogenously. The models therefore take into account percent cooling, the change in climate-sensitive building attributes, and the change in energy expenditures.

Armed with these empirical models, we explore in Section 4 how climate change might affect California in the future. Six uniform climate change scenarios are examined based on results from many general circulation models (GCMs). Two specific GCM runs are also employed: the Hadley model (Johns et al., 1997), a wet scenario, and the parallel climate model (PCM; Dai et al., 2001a, 2001b), a dry scenario. Using the economic growth scenarios for the California project, we predict the baseline energy expenditures for each county in the state. The baseline is a function of population growth, per capita income, building modernization, and cooling penetration. We then predict the energy impacts (changes in energy expenditures) in each county in California for each climate scenario. Changes to energy supply from changes in hydroelectricity are estimated separately in Appendix VII. Even adjusting for the population in each county, we expect that impacts will vary across the state. The current climate varies significantly across counties in California depending on latitude, proximity to the Pacific Ocean, and altitude. Counties that are currently warmer are more likely to be harmed by further warming, whereas counties that are currently cool may benefit (at first).

2. Theoretical Model

We follow the general methodology pioneered by Morrison and Mendelsohn (1999). Climate change is expected to alter the choices among energy and building characteristics that are derived from the demand for interior temperature. To illustrate this decision process in the residential and commercial energy sectors, separate models are developed for households and firms. We take a partial equilibrium approach to this problem and build a model of energy demand independent of other sectors of the economy. Although a general equilibrium approach would be able to capture interactions among the energy sector and other climate sensitive parts of the economy, these interactions are expected to be small, suggesting that such an effort would not be warranted. For example, Mendelsohn and Neumann (1999) estimate that the magnitude of economic impacts on the U.S. economy from climate change is expected to be less than 0.3% of gross domestic product (GDP). If impacts are indeed this small, there will be only small changes in prices and negligible general equilibrium impacts. There is, however, an important interaction between energy impacts and carbon abatement programs that should be considered in future studies, but this is beyond the scope of this work.

2.1 Residential Model

In the residential model, individuals are assumed to choose expenditures for energy, building characteristics, and all other goods to maximize utility subject to a budget constraint. Utility is assumed to be dependent on interior temperature, T, and on an index of all other goods, R. T is assumed to be a function of climate, C, energy use, Q, and building characteristics, Z. The budget constraint exhausts income, Y, on purchases of all other goods, energy, and building characteristics where the price of all other goods is normalized to 1 and P_q and P_z are the prices of energy and building attributes, respectively. The household problem is to choose the level of Q, Z, and R, given climate:

$$\max_{Q,Z,R} \; U(T,\; R) \qquad \text{s.t.} \quad \begin{aligned} & R + P_q \cdot Q + P_z \cdot Z = Y \\ & T = f(C,Q,Z) \end{aligned} \tag{1}$$

$$\text{where: } \quad C < T^*(heating) \Rightarrow T_Q > 0, T_{QQ} < 0 \qquad C > T^*(cooling) \Rightarrow T_Q < 0, T_{QQ} > 0$$

$$T_Z > 0, T_{ZZ} < 0 \qquad\qquad T_Z < 0, T_{ZZ} > 0$$

$$T_{QZ} \, ?\, 0, T_C > 0 \qquad\qquad T_{QZ} \, ?\, 0, T_C > 0$$

with T^* representing optimal interior temperature and subscripts representing first and second partial derivatives. We assume that people must cope with both a heating and cooling season during a year. During the heating season, the desired interior temperature is assumed to be higher than the outside temperature so that expenditures on both energy (Q) and buildings (Z) increase interior temperatures. During the cooling season, expenditures are needed to reduce interior temperature. An increase in ambient temperature (C) during the heating season consequently reduces expenditures needed to achieve a given interior temperature. An increase in ambient temperature during the cooling season, in contrast, requires more expenditure by the household to maintain initial interior temperatures.

The relationship between energy and building expenditures may be different during the heating and cooling seasons. Building characteristics such as insulation and storm windows tend to reduce energy expenditures in both seasons. Insulating building attributes are substitutes for energy expenditures. If warming reduces the energy expenditures required to keep a home warm, the homeowner may well decide to spend less on building expenditures in the long run. Some of the long-run benefits from warming during the heating season will be taken as lower expenditures on building insulation. During the cooling season, warming will increase the demand for energy expenditures. In summer, further warming will likely increase expenditures on buildings for either insulation or added cooling capacity. The increased expenditure on buildings is part of the damages from warming during the cooling season. Increased expenditures on insulation will reduce energy expenditures, but increased expenditures on cooling capacity will increase energy expenditures.

Maximizing Equation 1 will lead to an optimal bundle of interior temperature, T^*, and all other goods, R^* given initial conditions. With climate change, individuals can respond by changing expenditures on energy, expenditures on building characteristics, or interior comfort levels. We assume that households have a desired interior temperature during the heating and cooling season. If households in the United States are wealthy enough to purchase this desired interior temperature regardless of outside temperatures, the welfare effect of alternative climates simplifies to changes in energy and building expenditures. If warming reduces overall household energy-related expenditures, warming will be a net benefit, but if it increases energy-related expenditures, warming will be a net damage. Note that in many economic analyses, an increase in demand is assumed to be beneficial, not harmful. In this work, however, increases in energy are not assumed to entail increases in utility. Higher energy expenditures imply a higher cost of achieving a specified interior temperature, not a higher level of comfort. Increases in cost are damages and decreases in cost are benefits.

In both the residential and commercial models, we predict the probability that the occupants will cool their building. The analysis takes a logit functional form, fitting an S-shaped probability to the data:

$$\Pr(\text{cool}) = \exp(\sum BX)/(1+\exp(\sum BX)) \tag{2}$$

We estimate a separate cooling regression for residential and commercial buildings, then use the results from these regressions to predict the fraction of buildings that are cooled in each climate scenario.

In this study, we assume that households maintain their desired interior temperature. Despite the wide range of outside winter temperatures across the United States, households keep interior winter temperatures almost identical across the country (EIA, 1992). If households move away from (toward) their desired interior temperature as climate changes, there will be an additional welfare loss (gain) not reflected in energy-related expenditures. In this case, the change in climate will cause a reduction (increase) in utility associated with moving away from (toward) the ideal interior temperature. Changes in energy expenditures will underestimate the true change in welfare; they will underestimate both the damages and the benefits of climate change.

Earlier cross-sectional studies suggested that homeowners do not cool as much as expected in hot northern summers (Morrison and Mendelsohn, 1999). The results suggested that people endure reduced interior comfort if summers are relatively short. Because Morrison and Mendelsohn (1999) assumed that cooling would be unaffected by warming, they probably underestimated the damages from warming in the summer. In this study, we explicitly predict how cooling will change with warming in the residential sector. The empirical model suggests that warming will encourage people to adopt cooling throughout the residential market. Because this will reduce the current discomfort of warm summers, it will mitigate some of the unmeasured welfare effects in the earlier studies. By including the probability of cooling, the study will do a better job of measuring the welfare effects.

If people maintain interior temperature regardless of climate, they will respond to warming by adjusting energy expenditures alone in the short run and building and energy expenditures in the long run. Fully differentiating the interior temperature production function and setting the sum to zero:

$$T_C\, dC + T_Q\, dQ + T_Z\, dZ = 0 \tag{3}$$

Equation 3 describes the change in building and energy expenditures required to compensate for a change in climate. The welfare impacts of climate change on energy can be described as the change in income necessary to pay for the change in energy and building expenditures:

$$dY/dC = P_Q\, dQ + P_Z\, dZ \tag{4}$$

If warming increases (decreases) energy expenditures, welfare falls (rises) by the required change in expenditures.

2.2 Firm Model

A parallel model to the household can be constructed for the firm. Instead of maximizing utility, however, the firm maximizes profit. Rather than being constrained by income, the firm is constrained by its production possibility set. This represents the combination of inputs and outputs that are feasible given the production technology. Assuming firms take prices as given exogenously in factor markets, the firm chooses the combination of energy, *Q*, building characteristics, *Z*, and all other inputs, *X*, that minimizes costs subject to its possible production:

$$\min_{Q,Z,X} P_q \cdot Q + P_z \cdot Z + P_x \cdot X \qquad \text{s.t.} \quad g(Q, Z, X) = y \tag{5}$$

where *Q* and *Z* are interior temperature inputs, P_q, P_z, and P_x are respective prices, and y is output. The firm must choose the optimal level of interior temperature and all other inputs that will minimize costs while ensuring production of chosen output *Q*. Solving Equation 4 for the optimal combinations of *Q*, *Z*, and *X* yields the well-known economic principle that firms will equate the technical rate of substitution with the economic rate of substitution:

$$\frac{P_q}{P_z} = \frac{g'(Q)}{g'(Z)}\,. \tag{6}$$

Interior temperature measurements suggest that many firms maintain the same interior temperature in both summer and winter across the entire United States. The expenditure necessary to maintain firm profits at their original level is consequently equal to the change in building and energy expenditures needed to maintain interior temperature:

$$dY/dC = P_Q\, dQ + P_Z\, dZ \quad \text{s.t. } T_C\, dC + T_Q\, dQ + T_Z\, dZ = 0 \tag{7}$$

In this study, the probability of cooling is also estimated for the commercial buildings. Because this probability changes with warming, including it in the model will help address the same biases with respect to changes in interior temperatures that we discussed in relation to the residential sector. Given this improvement in the model, changes in energy-related expenditures are likely to be accurate measures of both the benefits and damages from warming in the commercial sector.

3. Sources and Methods

3.1 Data

This study relies on data from the U.S. Department of Energy's 1989 Commercial Buildings Energy Consumption Survey (EIA, 1993) and 1990 Household Energy Consumption and Expenditures Survey (EIA, 1992). These surveys provide detailed data on annual energy expenditures and consumption as well as demographics, building characteristics, and climate. The data record choices made for several thousand buildings distributed in random clusters across the continental United States. This sample is weighted to represent the true population of buildings. These weights make it possible later in the analysis to extrapolate from the sample to the population as a whole. One important weakness of this information is that it reports only a single year of expenditures. The energy data reflects the weather of a single year. Ideally, we would want a longer time series of data to capture climate effects.

Although we might think at first that a more local data set would be preferable, there is no way to identify California residents in this data set, so this analysis relies on the entire continental U.S. data set. Further, explorations with just Pacific region data suggest that there is not enough variation in climate to obtain accurate coefficient estimates. For these reasons, we rely on data from the entire country to estimate climate sensitivity. This introduces some potential error from unknown factors that might be correlated with climate across the country but that would not be present in California.

Another limitation of the survey is the reported annual weather data that are available. The weather data in the original energy survey did not have measures of climate (long-term measures of weather); the data simply described the weather in the year of the survey. This study relies on special data that the EIA created for Morrison and Mendelsohn (1999). The public energy survey data was matched with climate data by county from Mendelsohn et al. (1994). Each observation has detailed climate data that are not available in the public survey file. The climate data are long-term (30 year) measurements of temperature and precipitation in each of two months: January and July. The reliance on climate data and not annual weather is an important distinction. Obviously, owners adjust energy expenditures to annual conditions, spending more on energy in cold winters and hot summers. However, because weather changes from year to year, owners do not customize their buildings to endure annual weather. All long-range adjustments are more likely to be keyed to climate, or long-term weather. The results in this study are thus expected to be different from cross-sectional energy studies that have looked only at annual weather (such as Baxter and Calandri, 1992; or Belzer et al., 1996).

The study relies on total energy expenditures by firms and households. This differs from several cross-sectional studies of electricity demand (for example, Baxter and Calandri, 1992; and Sailor, 2001). The electricity studies have certain advantages in that they explain the demand for a specific fuel. However, electricity studies alone will overestimate the damages from warming because electricity has a disproportionate share of cooling costs but a smaller share of heating costs. Electricity studies therefore capture the damages from more cooling but they do not fully capture the benefits from less heating.

The reliance on county measures of climate is not perfect. In order to protect confidentiality, the Energy Information Administration added a small error term to the climate data. There is an additional error term from using county-based climate measurements. Some counties are quite large, particularly in California, and actually have a range of climates within their borders.

Another limitation of the data is that energy is not divided between energy needed for temperature control and energy needed for other purposes. We assume in this analysis that the energy households and firms use for other purposes is not correlated with climate. Efforts to control for the size of buildings and their use hopefully keep many of these factors under control if they do in fact vary with climate.

3.2 Feasible Climate Change Measure

The welfare measure derived in the previous section suggests that the energy impacts from climate change can be captured by the change in cooling and energy expenditures. In the short-run analysis, we hold building characteristics constant by including all of them in the multiple regression. Energy expenditures are regressed on all building characteristics and climate.

In the long-run analysis, we want to allow climate-sensitive building characteristics to adjust. We begin by determining which building characteristics are climate sensitive. Regressing individual building features on climate, we can determine which building features vary from one climate zone to another. In the long-run model, climate-sensitive building characteristics are dropped from the regression. This allows them to adjust endogenously across climate zones. The climate coefficients in the long-run energy regression include endogenous shifts in building characteristics.

The difference between the short-run and long-run measures indicates how important building adjustments are likely to be. If short-run and long-run measures are similar, building adjustments are likely to be small. If the disparity between short- and long-run adjustments using energy alone is large, however, building adjustments are important.

3.3 Econometric Specification

The probability of cooling is estimated with a logit regression (Equation 2). Insignificant coefficients are dropped from the model. Several empirical models are then estimated to measure how energy expenditures in residential and commercial buildings vary with climate. The expenditure equation is assumed to be separable in energy and all other goods. Ordinary least-squares regression analysis is used to estimate total expenditures on all fuels as a function of climate, demographic and firm-specific information, and building characteristics.

Climate-sensitive characteristics are determined by regressing building characteristics on climate. The results show that the size of the home, the number of doors and windows, a wood-burning stove, a basement, inadequate insulation, discounted electricity rates, central air-conditioning, air-conditioning units, electric radiator heat, and the availability of natural gas are all residential characteristics that vary with climate. The empirical work also identifies that air ducts for heating, air ducts for cooling, boilers, heat pumps for cooling, buildup of roof material, metal roofs, shingle walls, the number of floors, and the use of alternative fuels are all commercial characteristics that vary with climate. Note that some of these characteristics reflect overall space conditioning energy demand, some affect insulation, and some reflect heating and cooling capacity.

A log-log functional form is used for the estimation because (1) it provides the highest predictive power based on F-tests of the overall significance of the regression, (2) it is commonly used in the energy demand literature, and (3) it yields the expected proportional relationship between the continuous variables and energy expenditures. The climate variables are included in both linear and squared form to reflect the hypothesized quadratic climate-expenditure relationship. The mean of the climate variables has been subtracted from each climate measure. Consequently, the estimated coefficient (β_0) on the linear term (C) in the regression model (Equation 7) can be interpreted as the marginal impact of that climate variable on energy expenditures evaluated at the mean of the sample.

The hypothesized expenditure equation for the short-run demand for energy is:

$$\ln \sum_{i=1}^{F} E_i = \alpha + \beta_0 C + \beta_1 C^2 + \beta_2 \ln P + \beta_3 \ln S + \beta_4 \ln Z_{nc} + \beta_5 D_{nc} + \beta_6 \ln Z_c + \beta_7 D_c \qquad (8)$$

where $i = 1$, F represents the total number of fuels, E_i is energy expenditures, C is a vector of climate variables, P is a vector of average fuel prices, S is a vector of demographic (firm-specific) characteristics, Z is a vector of building characteristics, and D is a vector of dummy variables. Subscripts c and nc represent portions of the vectors Z and D that are climate sensitive and nonclimate sensitive, respectively.

We explored several alternative methods of measuring climate in this analysis. Following the literature, cooling and heating days were analyzed first. These measures proved to be sensitive to the base temperature from which cooling and heating days were measured. Further, because we were eager to relate our energy research to measures relatively accessible from climate models, we turned to using monthly normal temperature and precipitation. These are 30 year averages of temperature and precipitation for a specific month. We explored using January, April, July, and October, but found the four monthly variables to be highly correlated. We followed Morrison and Mendelsohn (1999) for the commercial sector and used the annual temperature and the difference between winter and summer. For the residential sector, we used winter and summer climate, the temperature and precipitation in January and July. We found that these two different climate measures give the most sensible results for these two sectors.

The long-run model omits the climate-sensitive building characteristics, allowing these characteristics to be endogenous. The resulting impact captures how energy expenditures would change as building characteristics change freely as well.

$$\ln \sum_{i=1}^{F} E_i = \alpha + \beta_0 C + \beta_1 C^2 + \beta_2 \ln P + \beta_3 \ln S + \beta_4 \ln Z_{nc} + \beta_5 D_{nc} \qquad (9)$$

These equations are estimated using microdata for individuals and firms. Because the data come from individual households and firms and are not aggregate, we did not expect identification to be a problem in this study. This contrasts with many energy studies that rely on aggregate data, where prices would be endogenous. With disaggregate data, we can reasonably assume that prices are exogenous to each home or firm and that prices are given. However, prices can be a problem in locations with nonlinear price schedules. For this study, we used average prices calculated by dividing energy expenditures by quantities consumed.

4. Empirical Results

Table 1 presents the logit results for the probability that central cooling is installed in residential properties. The coefficients in Table 1 are generally well behaved. Higher prices for fuels used for cooling reduce the probability of cooling. Newer buildings are much more likely to cool. Larger buildings are more likely cooled. Homeowner attributes such as higher income and age (over 65) increase the probability of cooling, but factors such as the tenant controlling the heat, the age of the head of household, cash aid, and family size all decrease the probability of cooling. Residential building characteristics such as the number of units, the number of floors, color TV, and more appliances all increase the chance the building is cooled.

Table 1. Logit regression of residential probability of cooling

Variable	Coefficient t-statistic	Variable	Coefficient t-statistic
Constant	797 (20.41)	Log # floors	0.21 (1.92)
January temperature	-9.03e-3 (1.27)	Log family size	-0.78 (9.34)
January temperature^2	4.50e-3 (6.46)	Log age of household head	-0.31 (2.15)
July temperature	0.43 (20.41)	Multiple units	0.87 (6.34)
July temperature^2	-3.79e-2 (9.36)	Tenant controls heat	-0.95 (2.27)
Log electricity price	-0.76 (4.88)	Over 65	0.26 (1.92)
Log natural gas price	-0.84 (5.47)	Cash aid	-1.31 (2.11)
Log year built	103 (20.11)	TV color	0.36 (7.98)
Log income	0.63 (10.52)	Appliances	0.88 (6.42)
		Log of rooms	1.81 (11.07)
Observations	**5,030**	**Log likelihood**	**-2,166**

Table 1 suggests that, as expected, residential cooling increases sharply with summer temperatures. The probability of cooling, however, increases at a decreasing rate as temperatures rise. Mean winter temperatures in the United States have little effect on the probability of residential cooling. However, the probability of cooling increases at an increasing rate as winter temperatures warm above the mean. Winter temperatures have a role in cooling because they reflect how long temperatures will remain warm throughout the year. Surprisingly, southern counties are not hotter than northern counties in August but they remain hot for much longer. The length of the hot season figures prominently in Americans' choice of cooling equipment. Precipitation has no effect on the probability of residential cooling.

Table 2 presents the results of the logit cooling regression for the commercial sector. Higher prices for electricity and natural gas both reduce the probability of cooling because these are the two fuels used for cooling. More modern buildings, as well as buildings used for food, health, laboratories, offices, and retail are more likely to cool. Interestingly, larger buildings are more likely to be cooled despite the fact that they are more expensive to cool. This implies that many buildings that are not cooled house relatively small operations, such as neighborhood offices and retail spaces. Buildings such as warehouses are also often not cooled.

Table 2. Logit analysis of commercial cooling

Variable	**Coefficient** **t-statistic**	**Variable**	**Coefficient** **t-statistic**
Constant	-139 (7.30)	Log year built	17.77 (7.04)
January temperature	-4.29e-2 (4.38)	Food sales and service	9.76e-3 (6.59)
January precipitation	0.14 (6.57)	Warehouse	-6.98e-3 (7.17)
July temperature	0.22 (12.66)	Health facility	11.6e-3 (5.34)
July precipitation	-0.13 (6.92)	Outpatient health	9.51e-3 (4.46)
July precipitation^2	4.14e-2 (4.18)	Laboratory	8.68e-3 (2.92)
Log electricity price	-0.25 (2.88)	Office	12.5e-3 (13.51)
Log natural gas price	-0.31 (4.17)	Retail	28.6e-3 (3.31)
Log square feet	0.33 (16.44)	Urban area	0.15 (1.94)
Observations	**5,611**	**Log likelihood**	**-3,231**

Table 2 also reveals the connection between commercial cooling and climate. Higher July temperatures increase the probability of cooling, but higher January temperatures actually reduce cooling probabilities. The commercial sector, relative to the residential sector, seems more responsive to the severity of temperature in the summer rather than the length of the period it is hot. Cooling in the commercial sector is also sensitive to precipitation. Higher summer precipitation has a U-shaped relationship with cooling, at first reducing cooling, but then increasing it. Higher winter precipitation increases cooling. These relationships may reflect the interaction between heat and humidity. The higher the humidity, the more unpleasant the high heat, and thus the greater the demand for cooling.

Table 3 presents the OLS regression results for the short-run and long-run versions of the residential model. The dependent variable is the log of total energy expenditures. The control variables in the residential sector are well behaved. Because the dependent variable is expenditures, not quantity demanded, price elasticity must be calculated from the estimated coefficients. Note that predicted elasticities based on average rates are expected to be biased, but Halvorsen (1975) demonstrated that with a double-log form, elasticity estimates for marginal and average rates are quite comparable. Two-stage least-squares regression analysis was used to test for the importance of nonlinear price schedules. Prices were regressed on a set of demand variables and then the predicted price was used in the expenditure regression. The 2SLS models had similar climate coefficients to the OLS models but the price coefficients behaved poorly. The estimated price elasticities fall within the predicted range of the literature from -0.5 to -2.0 (see Wilson, 1971; Anderson, 1973, Halvorsen, 1975; Barnes et al., 1981; and Baker et al., 1989). The residential estimates are -0.7 for electricity, -0.8 for natural gas, and -1.1 for liquefied petroleum gas (LPG). Demographic characteristics that positively influence residential energy expenditures include income, family size, age of household head, tenant controlling the heat, and receipt of heating vouchers. Note that having the tenant control the heat is not the same as having the tenant pay for heat separately. Expenditures are less if the head is Hispanic, receives cash aid for heating (measure of poverty), participates in an energy discount program, or burns wood as an alternative fuel. Structural characteristics that positively influence expenditures include home area, the number of rooms, the number of doors and windows, the age of the house, and inadequate insulation. The presence of a basement, the more residential units in the property, and the more floors all reduce energy expenditures. Appliances and electrical equipment such as a TV, a computer, a dishwasher, a clothes washer and a clothes dryer increase energy expenditures. Space conditioning equipment including central air-conditioning, wall or window air-conditioners , and electric wall or radiator heaters also increase expenditures. Only some households have access to natural gas, but if this option is available, household expenditures are less.

Table 3. Residential model results — aggregate expenditure analysis

Variable	Short run	Long run	Variable	Short run	Long run
Constant	42.7 (8.27)	40.2 (8.65)	Log income	5.39e-2 (7.64)	7.88e-2 (11.05)
January temperature	-7.60e-3 (4.63)	-9.37e-3 (5.60)	Log # floors	-9.8e-2 (7.68)	-0.12 (9.23)
January temperature^2	-2.23e-4 (1.90)	-0.97e-4 (0.80)	Log family size	0.23 (23.64)	0.22 (22.17)
January precipitation	1.87e-2 (3.57)	2.30e-2 (4.24)	Log age of head	5.47e-2 (3.93)	7.69e-2 (5.40)
January precipitation^2	-1.63e-3 (2.39)	-1.84e-3 (2.62)	Multiple units	-9.70e-2 (5.81)	-9.95e-2 (6.32)
July temperature	1.19e-2 (3.49)	1.87e-2 (5.47)	Tenant controls heat	0.17 (4.31)	0.22 (5.17)
July temperature^2	2.48e-3 (4.96)	2.43e-3 (4.74)	Hispanic	-4.61e-2 (2.46)	-6.20e-2 (3.19)
July precipitation	2.03e-2 (4.99)	2.94e-2 (7.09)	Cash aid	-0.19 (3.90)	-0.20 (3.85)
July precipitation^2	-4.56e-3 (2.95)	-5.95e-3 (3.72)	Heat aid	6.69e-2 (2.59)	6.03e-2 (2.25)
Log electricity price	0.33 (17.88)	0.33 (17.57)	TV color	6.09e-2 (11.09)	7.32e-2 (12.99)
Log natural gas price	0.17 (8.58)	0.19 (9.53)	Computer	4.00e-2 (3.03)	5.14e-2 (3.75)
Log LPG price	-8.9e-2 (4.02)	-7.9e-2 (3.45)	Appliances	0.10 (7.12)	0.14 (9.64)
Log year built	-4.96 (7.31)	-4.55 (7.41)	Log of rooms	0.12 (5.02)	0.36 (18.94)
Log home area	.018 (12.38)	—	Electricity discounts	-7.17e-2 (2.61)	—
Wood burning stove	-5.09e-2 (4.33)	—	Central air conditioning	0.15 (11.03)	—
Log doors and windows	8.41e-2 (6.02)	—	Wall or window air conditioner	4.10e-2 (3.50)	—
Basement	-9.47e-2 (7.14)	—	Electric wall heater	9.05e-2 (6.80)	—
Poor insulation	4.04e-2 (3.42)	—	Natural gas available	-4.96e-2 (4.40)	—
Observations	5,030	5,030	Adjusted R^2	0.97	0.96

Note: T-statistics are in parentheses.

The following variables were found to be climate sensitive in the residential analysis: home area, wood-burning stove, number of doors and windows, basement, poor insulation, discount electricity, central air-conditioning, window air-conditioning, electric wall heat, and natural gas availability. These variables were included in the short-run regression but omitted from the long-run regression. The long-run model allows these variables to change endogenously with climate.

Table 4 presents the short-run and long-run commercial results. The commercial price elasticity estimates fall within the range most commonly cited in the literature, -1.0 to -3.0 (Baughman and Joskow, 1976; Mount et al., 1993). The specific price elasticities predicted in this study are -1.5 for electricity and -1.1 for natural gas. Characteristics of the commercial operation that positively influence expenditures include the number of months the business is open per year; the various building uses; and the presence of appliances such as ice, water, or vending machines, and commercial refrigerators and freezers. Warehouses that are not refrigerated and tenants that control the heat, for example, reduce energy expenditures. Building characteristics that increase energy expenditures include square footage, number of floors, and built-up roof material. Buildings that are more modern use more energy, which is an interesting result because it suggests that the greater demand for energy exceeds any efforts to install more insulation and other conservation features. Glass and metal roofing materials lower expenditures, as do wall materials such as masonry and shingles. All space conditioning equipment causes expenditures to be higher, except heat pumps for cooling, which lower expenditures. Buildings that use alternative fuels have lower energy expenditures.

In the commercial analysis, the following variables are climate sensitive: air ducts for cooling, air ducts for heating, boilers, heat pump for cooling, built-up roof material, metal roof, number of floors, and alternative fuel use. These variables are included in the short-run regression but are excluded from the long-run regression.

Climate-Expenditure Relationship

Residential climate is represented in terms of January and July temperature (degrees C) and precipitation (inches per month). We tried alternative specifications, but they yielded inferior results. For example, we explored an earlier functional form using annual temperature and winter-summer differences. However, precipitation was not significant in that analysis and the regression did not provide any clear results for winter and summer effects (Morrison and Mendelsohn, 1999). We also tried adding April and October climate variables, but we were unable to estimate sensible coefficients for this many highly correlated variables. Our analysis has the advantage of including precipitation effects and the effect of winter (heating) versus summer (cooling) on total energy expenditures.

Table 4. Commercial model results — aggregate expenditure analysis

Variable	Short run	Long run	Variable	Short run	Long run
Constant	-50.2 (5.63)	-35.9 (5.21)	% laboratory	9.89e-3 (6.71)	9.88e-3 (6.48)
Average temperature	-1.67-2 (3.26)	-1.69e-2 (3.39)	% industry	13.4e-3 (3.96)	13.7e-3 (3.91)
Average temperature^2	3.28e-3 (4.60)	3.59e-3 (4.90)	% office	4.22e-3 (9.62)	5.68e-3 (12.81)
Standard temperature	1.33e-2 (2.90)	1.59e-2 (3.37)	% retail	2.81e-3 (7.51)	2.74e-3 (7.33)
Standard temperature^2	-0.62e-4 (0.17)	-0.56e-4 (0.15)	% education	2.76e-3 (4.89)	3.44e-3 (5.98)
Log electricity price	-0.50 (16.05)	-0.50 (15.65)	Metropolitan	0.35 (12.47)	0.45 (16.16)
Log natural gas price	-0.08 (2.78)	-0.12 (3.97)	Ice machine	0.49 (17.73)	0.54 (18.87)
Masonry wall	-0.76 (4.05)	-0.73 (3.74)	Commercial refrigerator	0.45 (12.54)	0.49 (13.30)
Log square foot	0.53 (39.63)	0.59 (46.33)	Computer cooling	0.58 (10.90)	0.64 (11.63)
Months open/year	2.75e-2 (4.99)	2.49e-2 (4.38)	Heat pump for heat	0.14 (2.08)	8.63e-2 (2.10)
Log year built	6.71 (5.69)	4.76 (5.23)	Tenant controls heat	-0.14 (5.21)	-0.16 (6.08)
% food sale/serve	8.31e-3 (13.67)	8.54e-3 (13.69)	Roof glass	-1.77 (5.61)	-1.95 (5.98)
% nonrefrigerated warehouse	-3.27e-3 (7.23)	-4.01e-3 (8.89)	California dummy	0.37 (5.58)	0.36 (5.24)
% health	7.04e-3 (5.81)	8.33e-3 (6.67)	% outpatient	2.96e-3 (3.61)	3.82e-3 (4.52)
Air duct cooling	-22.8 (1.69)	—	Roof-metal surface	-0.15 (4.37)	—
Air duct heating	6.97e-2 (2.12)	—	Wall shingle	-0.17 (5.03)	—
Boilers	0.24 (6.64)	—	Log floors	0.14 (4.30)	—
Heat pump cooling	-0.14 (1.94)	—	Alternative fuel	-0.54 (11.89)	—
Roof built-up	0.13 (4.78)	—	Cooling*age	3.02 (1.70)	—
N	5,611	5,611	Adjusted R^2	0.96	0.96

Note: T-statistics are in parentheses.

In the residential sector (Table 3), warmer January temperatures reduce expenditures linearly in both the short- and long-run models. The warmer winter temperatures imply reductions in expenditures for heating. July temperatures have a U-shaped relationship with energy expenditures with a cost-minimizing temperature of 20°C. California is a few degrees warmer than this minimum temperature. Warming in the summer, then, will increase energy expenditures throughout most of California. Because the summer increase is larger than the winter decrease, warming will cause a net increase in annual energy expenditure for the average California residence. Both January and July precipitation positively influences expenditures at the mean, suggesting that more humid locations have higher energy expenditures. The effect of higher humidity increases our desire for both heating in the winter and cooling in the summer, and it also increases the cost of both. The squared terms for summer and winter precipitation are significant and negative, suggesting that this effect diminishes as humidity increases.

According to Table 4, warmer annual temperatures decrease energy expenditures at the U.S. mean. The squared term on temperature, however, is positive so that energy expenditures have an overall U-shape with respect to temperature. The cost-minimizing annual temperature is 15.8°C, which is 2.4°C above the U.S. average but below the average temperature for California. On average, warming will increase California commercial expenditures. The difference between summer and winter temperatures increases energy expenditures as expected. The greater this difference, the more that has to be spent on heating in the winter and cooling in the summer. The cost-minimizing temperature for the commercial sector is warmer than the cost-minimizing temperature for residential energy, and it is higher than what engineering models would suggest. Engineering studies suggest that commercial buildings have substantial waste heat from lights and other activities. The engineering studies predict that the minimum energy expenditures for commercial buildings should be less than those for residences. The cross-sectional observations, however, reflect the fact that residential owners do not invest in air-conditioning in the cooler north. Consequently, the cooler north has less residential energy expenditures than the south. Commercial buildings in the north, in contrast, do install air-conditioning, so the minimum energy location in the commercial sector is actually much further south (in warmer locations).

We examined a few other analyses of climate-energy interactions to test the robustness of the empirical results. For example, we limited the data to firms and households in the Pacific region and re-estimated the equations. Although the results were quite similar to the national results, many of the coefficients were less significant because of the reduced sample size. We also estimated the equations using data that likely come from California, but this led to unsatisfactory results for two reasons — we cannot determine precisely which state each observation comes from, and California has a limited range of climate variation. Consequently, the analysis relies on the national empirical results.

5. Climate Change Simulations

In the following simulations, the empirical relationships between today's climate and current energy expenditures are used to estimate how California might be affected in the future by climate change. Before examining climate effects, however, we must first adjust energy expenditures for economic growth. The most straightforward adjustment is for population. As California's population expands, we assume that energy consumption expands proportionately. We expand the population in each county using a high and low projection of state population in 2020, 2060, and 2100 as discussed in the baseline (Appendix II). We also make an adjustment for changes in buildings. As new buildings replace older ones, we expect that new energy features will replace old technologies. We capture this effect by updating the date that buildings are built in each time period. We expect that energy prices will increase over time as inexpensive deposits of fossil fuels become rare. We build a 1% per year increase into all fuel prices (for example, Manne and Richels, 1992, assume a 1.7% price increase in their business-as-usual case for nonelectric energy, although they assume electric prices will remain constant). Because future energy prices are difficult to predict, we also include a sensitivity analysis with no real price increases.

Economic development is expected to have a strong effect on baseline energy projections for the state without climate change. The baseline energy expenditures for each sector are projected in Table 5. The expenditures by 2020 are estimated to be about $21 billion in the residential sector and $15 billion in the commercial sector. These expenditures on energy are estimated to increase to $37 to $61 billion in the residential sector and to $16 to $24 billion in the commercial sector by 2100. These baseline changes capture changes in population, income, building age, energy prices, and cooling penetration.

We expect that cooling will continue to penetrate both the residential and commercial markets. Using the logistic functions in Tables 1 and 2, we predict the level of cooling that will result from the population, income, modern buildings, and prices in future periods in Table 6. Cooling is predicted to penetrate more completely in the residential market, reaching more than 80% of homes in California by the end of the century. In contrast, only a little more than half of the commercial buildings are expected to install cooling by 2100. The fact that cooling does not penetrate more completely into the commercial sector reflects the wide set of uses for commercial buildings. For example, warehouses are not likely to be air conditioned at all. Changes in cooling behavior are captured in the analysis by weighting future samples toward buildings with cooling.

Table 5. Projected baseline energy expenditures for California ($ billion)

	Year		
	2020	**2060**	**2100**
Residential			
Slow growth	20.9	30.9	36.7
Fast growth	21.5	38.4	61.2
Commercial			
Slow growth	15.1	16.9	15.7
Fast growth	15.1	19.7	24

Note: Scenarios include population growth, real energy price increases, income per capita, updated buildings, and increased cooling. Baseline assumes current climate.

Table 6. Percentage of future buildings with cooling in California

	Residential	**Commercial**
2020		
Slow growth	43.7	47.0
Fast growth	46.2	47.0
2060		
Slow growth	65.7	49.6
Fast growth	70.9	49.6
2100		
Slow growth	82.8	52.2
Fast growth	87.9	52.2

Source: From Tables 1 and 2.

Warming is expected to have an additional impact on the decision to install cooling. According to Tables 1 and 2, central cooling will be installed in more buildings as climates warm. Table 7 illustrates this point for three uniform incremental warming scenarios. The percentage of buildings that are cooled in the state clearly increases as the scenario warms. The residential sector is particularly responsive, increasing cooling installations in up to 99% of homes in the most severe warming scenario. Even the commercial sector is responsive, increasing cooling installation in up to 70% of the state's buildings in the most severe warming case.

Table 7. Effect of warming on percentage of buildings cooled by 2100

	Residential	Commercial
Baseline		
Slow growth	82.2	52.2
Fast growth	87.9	52.2
1.5°C		
Slow growth	90.5	58.0
Fast growth	93.9	58.0
3.0°C		
Slow growth	94.9	63.0
Fast growth	97.0	63.0
5.0°C		
Slow growth	97.6	70.0
Fast growth	98.7	70.0

Note: Assumes no change in precipitation.

The California study prescribes a large set of climate scenarios for all sectors. There are six uniform incremental scenarios for 2100 and six scenarios over time from two climate models, HadCM2 (Johns et al., 1997) and PCM (Dai et al., 2001a, 2001b). The uniform scenarios assume that temperature will increase by the same amount throughout the state and that precipitation will increase proportionately. Because the bulk of precipitation in California falls in the winter, most of the change in precipitation happens in the winter in all the scenarios. The climate model scenarios permit climate to change differently in each county and season. On average, the Hadley model predicts that by 2100, California temperatures could increase 4.2°C in winter and 3.8°C in summer and precipitation could increase by 72% in winter and 10% in summer. The PCM model predicts that by 2100, temperatures would increase by 2.1°C in summer and 2.6°C in winter and precipitation would decrease by 16% in winter and 51% in summer. The attachment provides the January and July temperature and precipitation changes for each county of California predicted for 2100 by the HadCM2 and PCM models.

For each climate prediction, the estimated regression equation in Table 1 is used to predict how residential cooling will change. These changes are then incorporated into projections of how energy expenditures will change. The new energy expenditures from each climate scenario are compared to the baseline energy expenditures for the same year. The change in energy expenditures is a measure of the welfare effect of the climate change. If people must increase their energy expenditures to maintain the same comfort level after warming, the increase in expenditures becomes a damage. If people can reduce their energy expenditures after warming, this reduction becomes a benefit.

Table 8 presents the results of these calculations for the residential sector. Two estimates are given. The short-run estimates freeze buildings as they are now. The long-run estimate allows the climate-sensitive characteristics of buildings to adjust endogenously. The difference between the two estimates provides a sense of the importance of adjusting buildings as a warming adaptation. The impacts of warming are expected to be harmful for the residential sector. In every uniform climate scenario, there are damages. These damages increase as the warming scenario increase in severity. For example, with slow growth, no precipitation increase, and the 1.5°C warming, long-run damages are 1.5 billion $/yr, but with the same conditions and a 5°C warming, long-run damages rise to 6 billion $/yr. The damages increase slightly when precipitation increases but the damages are quite sensitive to the baseline assumptions about economic growth. For example, the 5°C warming case leads to $6 billion with slow growth but $9 billion with faster growth.

Table 8. Annual California welfare impacts from climate change in 2100 residential energy ($ million)

Scenario	Short-run	Long-run
1.5°C, 0%P		
Slow	-1,609	-1,596
Fast	-2,154	-2,293
3.0°C, 0%P		
Slow	-3,158	-3,820
Fast	-4,306	-4,854
5.0°C, 0%P		
Slow	-5,440	-6,054
Fast	-7,735	-9,125
1.5°C, 9%P		
Slow	-1,764	-1,794
Fast	-2,411	-2,622
3.0°C, 18%P		
Slow	-3,462	-3,712
Fast	-4,807	-5,501
5.0°C, 30%P		
Slow	-5,934	-6,700
Fast	-8,545	-10,187

Notes: Negative numbers imply damages (increases in energy expenditures). P stands for precipitation.

Comparing the short-term and long-term results suggests that long-term impacts will generally be larger than those seen in the short term. When buildings can adjust to the warmer climates, the economic damages increase. We believe that this is caused primarily by an increase in cooling capacity that in turn leads to higher energy expenditures on cooling. Owners would change their buildings only if the benefits outweighed the cost. Adding central cooling increases energy expenditures so that long-run expenditures end up being higher than short-run expenditures. This increased energy expenditure must largely buy increased comfort. The difference in energy expenditures between the long run and short run, however, is not that large. It would appear that building adjustments are not important enough to include in the residential model.

The residential impacts of the GCM scenarios are presented in Table 9. Each GCM model provides estimates of climate change in 2020, 2060, and 2100. The resulting impacts fall within the range of impacts predicted by the uniform scenarios. The very wet Hadley scenario results in small damages in 2020 because climate has changed only slightly by then. However, by 2100, the impacts predicted by the Hadley model fall between the middle of the road wet and the more severely wet incremental scenarios. The PCM model predicts much gentler impacts both because precipitation declines and temperatures do not increase rapidly. By 2100, the impacts from the PCM fall between the middle of the road and the mildly dry incremental scenarios.

Table 9. Annual California welfare impacts from general circulation model scenarios on residential energy ($ million)

		Short-run	Long-run
Hadley			
2020	Slow	-1,824	-1,589
	Fast	-1,883	-1,653
2060	Slow	-3,589	-3,369
	Fast	-4,091	-3,954
2100	Slow	-4,219	-4,740
	Fast	-5,915	-7,099
PCM			
2020	Slow	-296	-189
	Fast	-310	-200
2060	Slow	-2,547	-2,234
	Fast	-2,903	-2,615
2100	Slow	-3,067	-2,947
	Fast	-4,010	-4,126

Note: Negative numbers imply damages (increases in energy expenditures).

The results for the commercial sector, shown in Table 10, are similar to the residential results. For mild warming, there are damages ranging from $300 to $900 million. With a large warming such as 5.0°C, damages rise to $3.9 to $8.7 billion. Energy expenditures are not identical in the short-run and long-run commercial models. Long-run damages are much larger than short-run damages. Clearly, the climate-sensitive building adjustments are resulting in higher energy expenditures, probably because of the increase in central cooling.

Table 11 presents the commercial results for the GCM scenarios. The Hadley and PCM models predict relatively small damages in 2020. These annual damages rise to $864 to $1127 million in the Hadley model by 2060 and to $611 to $797 million in the PCM model as temperatures rise. With the much large energy sector over time and the continued warming, damages are between $2.5-$4.5 billion by 2100 in the Hadley model and $1.5-$2.8 billion in the PCM model.

Table 10. Annual California welfare impacts from climate change in 2100 on commercial energy ($ million)

Scenario	Short-run	Long-run
1.5°C, 0%P		
Slow	-333	-503
Fast	-599	-906
3.0°C, 0%P		
Slow	-1,370	-1,791
Fast	-2,468	-3,226
5.0°C, 0%P		
Slow	-3,939	-4,850
Fast	-7,095	-8,736
1.5°C, 9%P		
Slow	-333	-503
Fast	-599	-906
3.0°C, 18%P		
Slow	-1,370	-1,791
Fast	-2,468	-3,226
5.0°C, 30%P		
Slow	-3,939	-4,850
Fast	-7,095	-8,736

Note: Negative numbers imply damages (an increase in energy expenditures). P stands for precipitation.

Table 11. Annual California welfare impacts from general circulation model climate scenarios on commercial energy ($ million)

		Short-run	Long-run
Hadley			
2020	Slow	-85	-140
	Fast	-85	-140
2060	Slow	-644	-864
	Fast	-840	-1,127
2100	Slow	-1,973	-2,522
	Fast	-3,553	-4,543
PCM			
2020	Slow	-47	-64
	Fast	-47	-64
2060	Slow	-453	-611
	Fast	-590	-797
2100	Slow	-1,172	-1,534
	Fast	-2,111	-2,763

Note: Negative numbers imply damages (increases in energy expenditures) and positive numbers imply benefits.

In Table 12, we add the residential and commercial results for a limited set of scenarios. We choose the 1.5°C, 9%P; the 3.0°C, 18%P; and the 5.0°C, 0%P scenarios. These three scenarios capture the full range of incremental scenarios tested. With damages in both the residential and commercial sectors, warming is strictly harmful to the California energy sector. Damages are in the $2.3-$3.5 billion range in the 1.5°C scenario and in the $10.9-$17.9 billion range in the 5°C scenario.

Table 12 also displays a sensitivity analysis. The previous analysis was based on the assumption that prices for energy would increase at 1% per year, but Table 12 explores an alternative scenario where energy prices are assumed to remain constant. When prices remain constant, the commercial energy sector grows larger and the residential energy sector gets smaller. The damages from warming in the commercial sector increase and the damages in the residential sector shrink. Commercial damages are smaller than residential damages in the 1.5°C case, about the same in the 3.0°C case, and much larger than residential damages in the 5.0°C case. Overall, the damages are smaller if real energy prices remain constant.

Table 12. Sensitivity analysis (million $/year)

	2100 climate scenario		
Case	**1.5°C, 9%P**	**3.0°C, 18%P**	**5.0°C, 0%P**
Price increases — slow growth			
Commercial	-503	-1,790	-4,850
Residential	-1,794	-3,712	-6,054
Total	**-2,297**	**-5,580**	**-10,904**
Price increases — fast growth			
Commercial	-906	-3,226	-8,736
Residential	-2,622	-5,501	-9,125
Total	**-3,528**	**-8,727**	**-17,861**
No energy price increase — slow growth			
Commercial	-463	-1,650	-4,468
Residential	-862	-1,880	-3,230
Total	**-1,325**	**-3,530**	**-7,698**
No energy price increase — fast growth			
Commercial	-834	-2,972	-8,048
Residential	-1,261	-2,838	-4,992
Total	**-2,095**	**-5,810**	**-13,040**

Note: Based on long-run coefficients from Tables 1 through 3. Negative numbers imply damages (increases in energy expenditures) and positive numbers imply benefits.

6. Conclusions

This study estimates several empirical models of the climate sensitivity of energy using a cross section of American firms and households. In this appendix, we argue that changes in energy in response to climate change provide a theoretically sound measure of welfare impacts. Increases in energy expenditures are clear damages and decreases are benefits if there are no significant changes in interior temperatures.

The empirical model predicts a notable increase in cooling in the summer with warming. This study improves on past cross-sectional studies by explicitly modeling the probability of cooling. We feel that this improvement mitigates one of the biases of the earlier studies, which did not take changes in summer interior temperatures into account.

The observed empirical relationship between climate and energy was expected. As winter temperatures rise, residential energy expenditures on heating fall. As summer temperatures rise, residential energy expenditures on cooling increase. Similarly, as average annual temperatures increase, commercial energy expenditures at first fall, but then rise as well, following a U shape. Theory predicts this observed U-shaped relationship between annual energy expenditures and outside temperature.

This work tests the importance of changes in buildings as part of the climate sensitivity of energy expenditures. We estimated both a short-run and a long-run model of energy expenditures. The short-run model freezes building characteristics in place. The long-run model allows climate-sensitive building characteristics to change with climate. By comparing the results of the two models, we can test whether the building changes are important. In both the residential and commercial sectors, the long-run damages are somewhat larger than the short-run damages. In the long run, both sectors spend more on energy as cooling capacity is increased. Because the long-run expenditures are greater than the short run costs, they are probably the more accurate estimate of the actual damages. The difference between short- and long-run results was small for the residential sector but larger for the commercial sector. This study suggests that it is important to model how commercial buildings might change as the climate warms.

We also tested how climate affects the probability that residential and commercial buildings have central cooling. Using logit analysis, we find that buildings are more likely to be cooled if they are in warmer climates. These empirical estimates are included in our analysis by weighting future samples of buildings to include more cooled structures.

Combining information about energy expenditures with the information about future conditions, we were able to predict how warming might affect California in the future. Warming is predicted to increase energy expenditures in residential and commercial buildings. With mild warming (1.5°C), the state damages range between $1.3 and $3.5 billion per year by 2100. With average warming (3°C), the damages range between $3.5 and $8.7 billion annually. Finally, with severe warming (5°C), the damages range between $7.7 and $17.8 billion annually. Two factors explain why the range of impacts is so large: the future growth of the state's economy and the future prices of energy.

The residential energy impacts across counties in the state are not uniform. Figures 1 through 3 are maps of the change in residential energy expenditures for the uniform scenarios of 1.5°C, 3.0°C, and 5.0°C, with no change in precipitation in 2100. Note that the predicted increases in energy expenditures in these maps are damages. Even in the three scenarios where climate change is assumed to be uniform throughout the state, the impacts vary depending on the initial climate of the county. For example, the northern maritime and high alpine counties exhibit small benefits from warming. The southern desert counties have the largest increases in energy expenditures. The remaining central valley and southern maritime counties have average state energy increases.

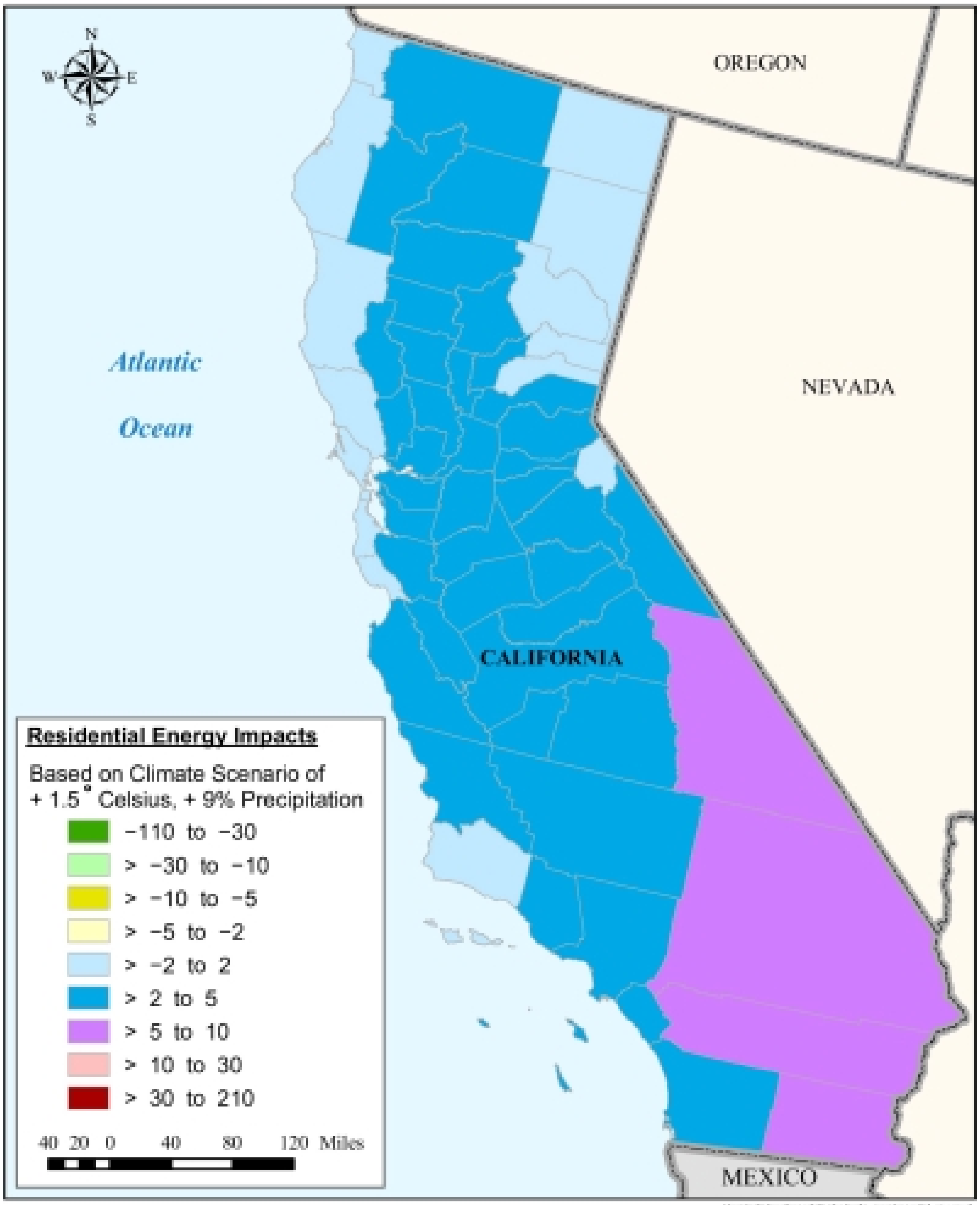

Figure 1. Percentage change in residential energy for a 1.5°C warming with 9% increase in precipitation

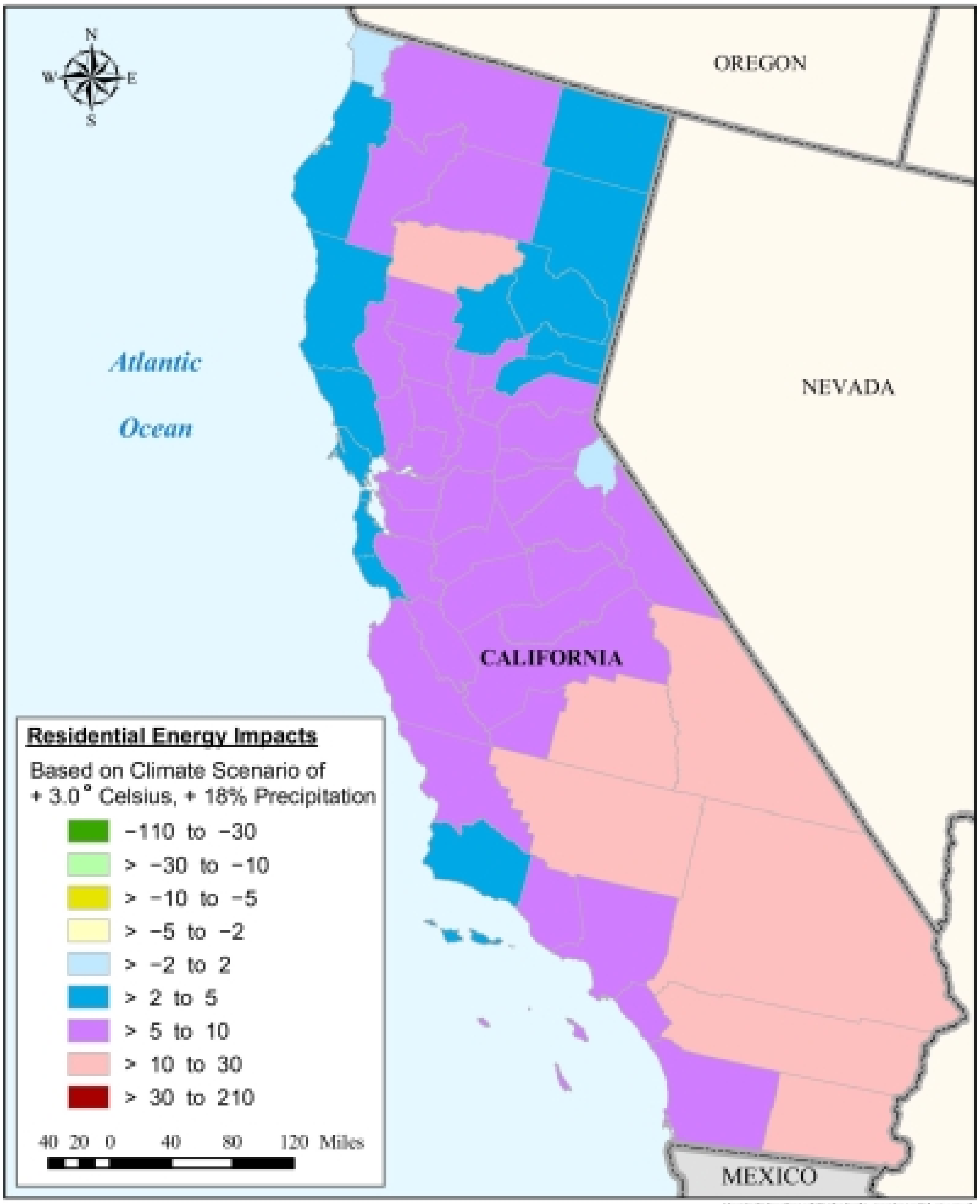

Figure 2. Percentage change in residential energy for a 3.0°C warming with 18% increase in precipitation

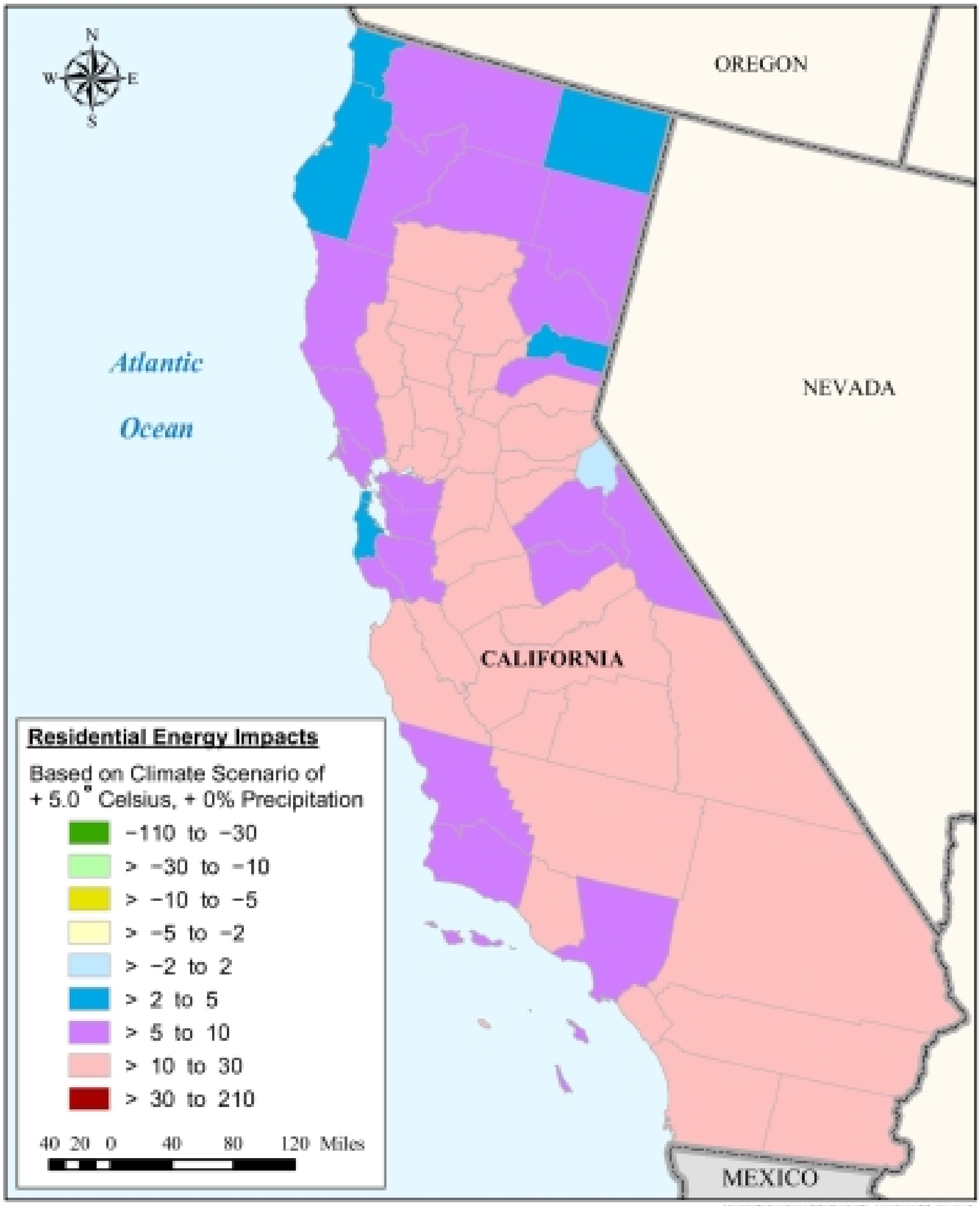

Figure 3. Percentage change in residential energy for a 5.0°C warming with no increase in precipitation

Figures 4, 5, and 6 are corresponding uniform scenario maps of the change in commercial energy expenditures. Reductions in energy expenditures are benefits and increases are damages. The results in the commercial sector are similar to the residential results. The northern maritime and alpine counties benefit from warming. The southern desert counties exhibit the largest damages per building. The central valley also suffers damages from warming, although these effects are smaller than in the desert. The southern maritime region also has small damages from warming.

This analysis gives a sense of the importance of climate change to the energy sector. The analysis suggests that California will experience an increase in both commercial and residential energy expenditures from warming. The resulting damages will increase as the warming becomes more severe. The size of the net impacts also depends on baseline assumptions about growth and energy prices. The impacts vary across counties, with the southern desert counties suffering the largest damages and the Central Valley also being damaged. The northern maritime and alpine counties, however, exhibit small benefits.

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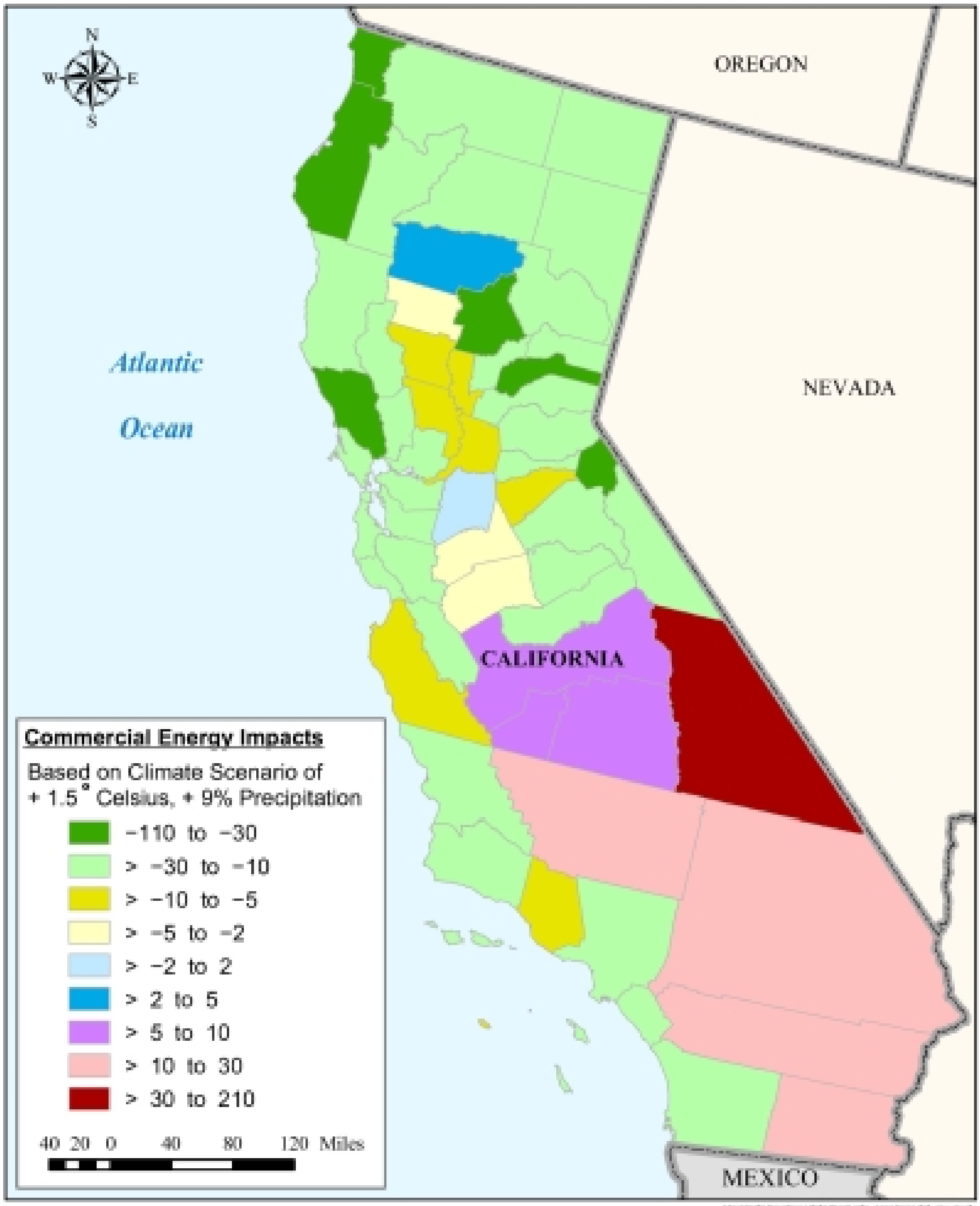

Figure 4. Percentage change in commercial energy for a 1.5°C warming with 9% increase in precipitation

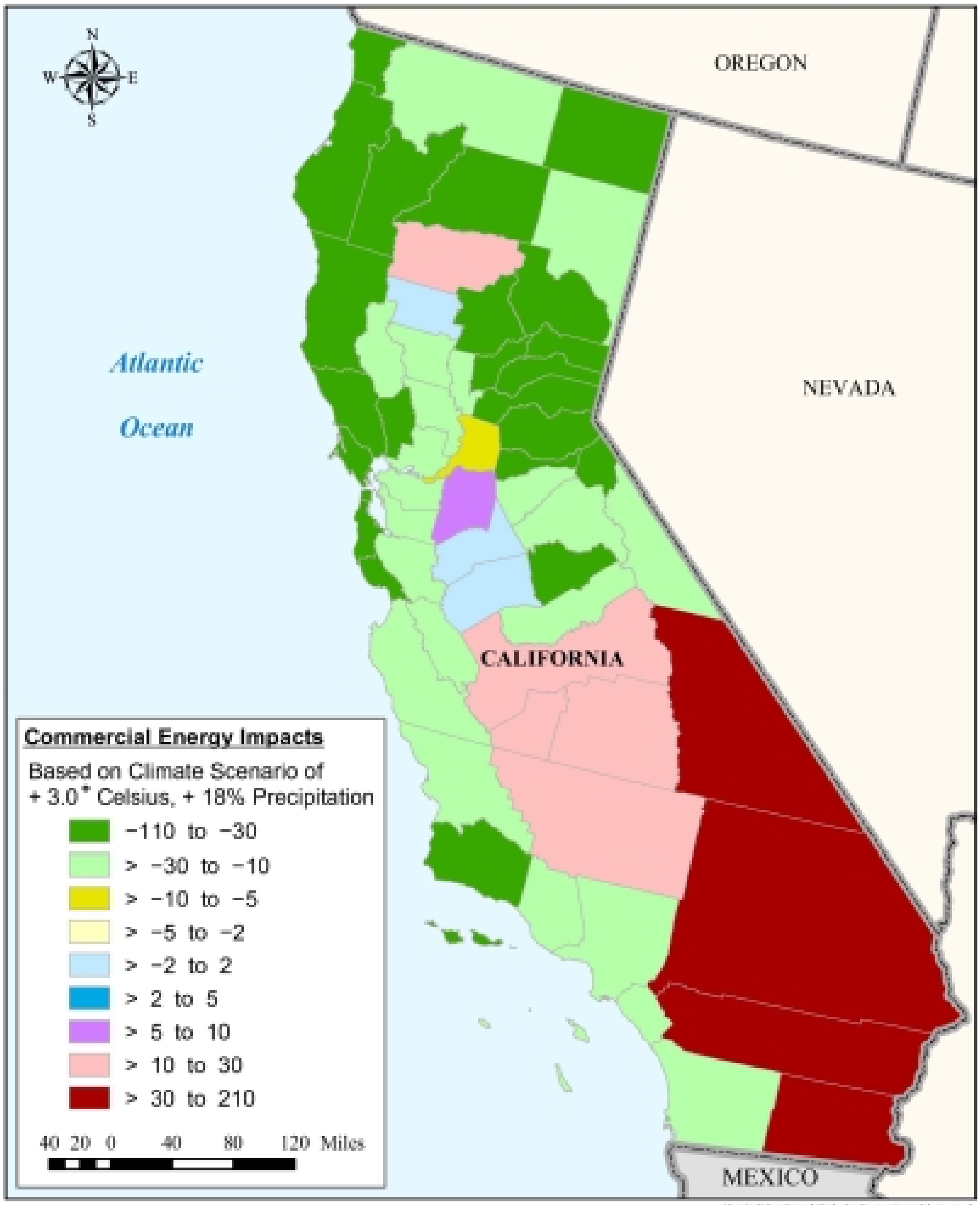

Figure 5. Percentage change in commercial energy for a 3.0°C warming with 18% increase in precipitation

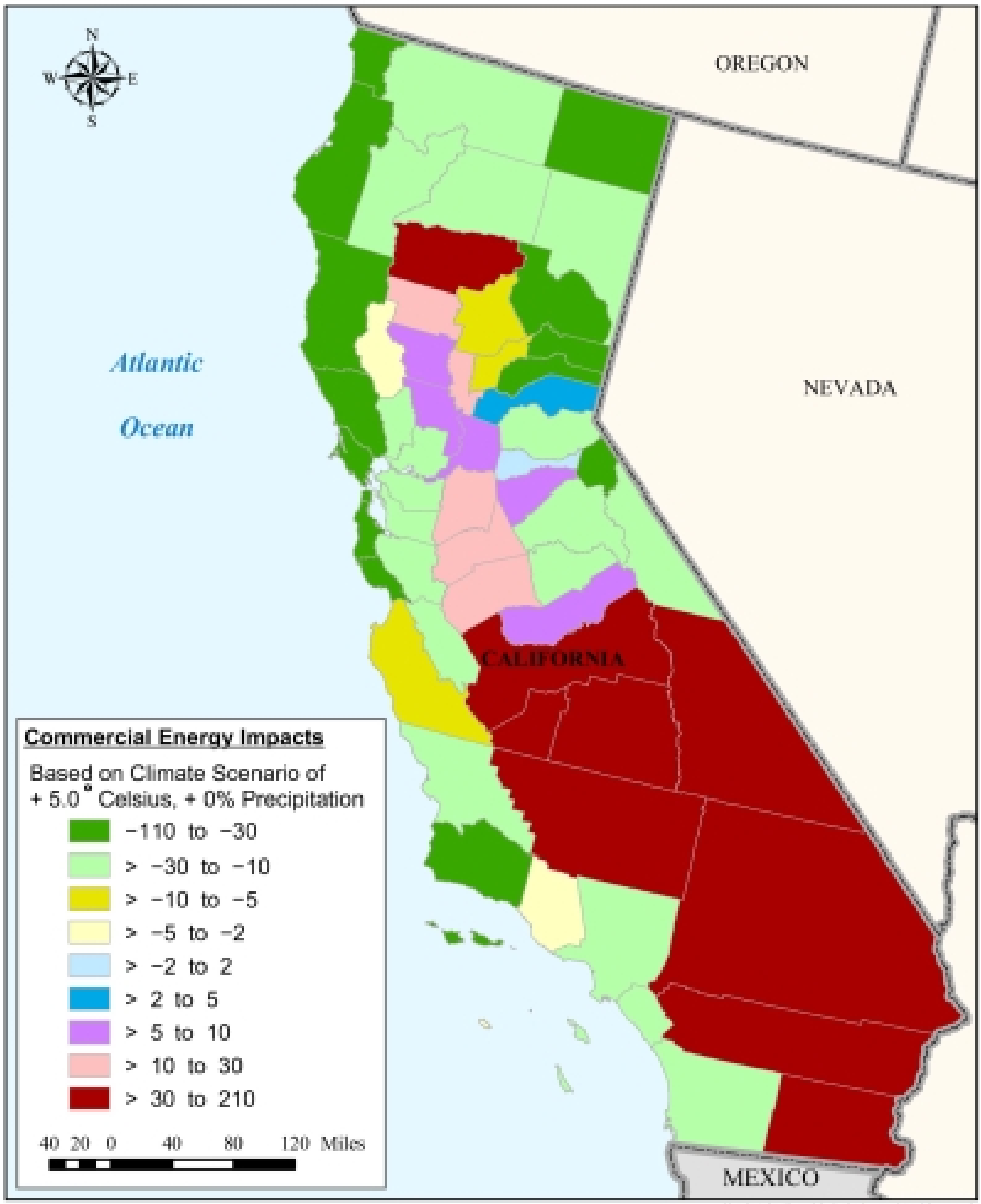

Figure 6. Percentage change in commercial energy for a 5.0°C warming with no increase in precipitation

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Appendix XI — Attachment

Data Definitions and Means

Table A.1. Definitions of independent variables: Residential regressions

Variable	Definition and mean
Age of head	Head householder age; 47.8
Basement	1 if home has basement, 0 otherwise; 0.30
White	1 if resident is white, or 0 otherwise; 0.97
Cash aid	1 if resident receives cash aid for heat, 0 otherwise; 0.01
Central AC	1 if household has central air conditioning, 0 otherwise; 0.36
Color TVs	Number of color TVs in household; 1.59
Computer	1 if household has computer, 0 otherwise; 0.15
Dish/cloth wash/dry	1 if home has dishwasher, clothes washer and dryer, 0 otherwise; 0.83
# doors/windows	Number of doors and windows in home; 14.4
Elec. wall — heat	1 if household uses electric wall units or radiators to heat, 0 otherwise; 0.22
Elec. price	Average electricity price; 0.087
Family size	Number of household members; 2.54
# floors	Number of floors in home; 1.4
Fuel oil price	Average fuel oil price; 1.02
Heat aid	1 if resident receives heating vouchers, 0 otherwise; 0.05
Hispanic	1 if resident is Hispanic/non-black, 0 otherwise; 0.07
Home area	Home area — square feet; 1837
Income	Average household income for relevant income range; 30,410
Elec. discount	1 if discounted or interruptible electricity rates, 0 otherwise; 0.01
Jan. temp	Average January temperature(demeaned) — degrees C; 0.5
Jan. precip	Average January precipitation(demeaned) — inches; 2.99
July temp	Average July temperature(demeaned) — degrees C; 23.8
July precip	Average July precipitation(demeaned) — inches; 3.38
ExpEnergy	Annual Energy Expenditures; 1177
Kero. price	Average kerosene price; 1.38
Lpg price	Average liquid petroleum gas price; 1.48
Metropolitan	1 if metropolitan statistical area, 0 otherwise; 0.32
Multiple units	1 if more than 1 unit, 0 otherwise; 0.25
Nat. gas price	Average natural gas price; 0.55
Nat. gas avail.	1 if natural gas is available, 0 otherwise; 0.75
Over 65	1 if age of head householder > 65, 0 otherwise; 0.20
Poor insulation	1 if household has inadequate insulation, 0 otherwise; 0.20
Portable kerosene	1 if household uses portable kerosene to heat, 0 otherwise; 0.004
# rooms	Number of rooms in home; 7.1
Tenant controls heat	1 if a tenant chooses heat, 0 otherwise; 0.15
Wall/window AC	1 if household has wall or window ac units, 0 otherwise; 0.32
Wood burning	1 if wood is burned as alternative heat source, 0 otherwise; 0.24
Year built	Year home constructed; 1961
California	1 if in state of California, 0 otherwise; 0.11

Table A.2. Definitions of independent variables: Commercial regressions

Variable	Definition
AC in computer room	1 if there is air conditioning in computer room, 0 otherwise; 0.20
Air duct-cool	1 if air ducts used for cooling, 0 otherwise; 0.50
Air duct-heat	1 if air ducts used for heating, 0 otherwise; 0.57
Alt. fuel used	1 if alternative fuel used, 0 otherwise; 0.05
Boilers	1 if boilers used for heating, 0 otherwise; 0.27
Refrigerator	1 if commercial freezer or refrigerator used, 0 otherwise; 0.32
Dist. heat price	Average district heat price; 8.20
Elec. price	Average electric price; 0.095
# floors	Number of floors; 3.0
Fuel oil price	Average fuel oil price; 0.81
Heat pump-cool	1 if heat pumps used for cooling, 0 otherwise; 0.13
Heat pump-heat	1 if heat pumps used for heating, 0 otherwise; 0.13
Ice/vending/wtr	1 if ice, vending or water machines used, 0 otherwise; 0.74
Jan. temp	Average January temperature(demeaned) — degrees C; 1.8
Jan. precip	Average January precipitation(demeaned) — inches; 3.0
July temp	Average July temperature(demeaned) — degrees C; 24.2
July precip	Average July precipitation(demeaned) — inches; 3.5
Metropolitan	1 if metropolitan statistical area, 0 otherwise; 0.81
Months open/year	Number of months open; 11.5
Nat. gas price	Average natural gas price; 0.87
% food sale/serve	Percent food sale and food service; 4.9%
% nonref wh/vac	Percent non-refrigerated warehouse and vacant; 13.3%
% health	Percent in-patient and skilled healthcare; 2.4%
% out patient	Percent out-patient healthcare and public safety; 1.1%
% lab/ref whs	Percent lab and refrigerated warehouse; 1.4%
% industry	Percent industrial: 0.5%
% office	Percent office; 20.6%
% retail/service	Percent retail/services; 20.7%
% educ	Percent education; 12.1%
Roof: built up	1 if roof material = built up, 0 otherwise; 0.45
Roof: glass	1 if roof material = glass, 0 otherwise; 0.007
Roof: metal surf.	1 if roof material = metal surface, 0 otherwise; 0.15
Sq. ft.	Building size — square feet; 99760
Tenant controls heat	1 if tenant controls heat, 0 otherwise; 0.55
Wall: masonry	1 if wall material = masonry/siding, 0 otherwise; 0.001
Wall: shingle	1 if wall material = siding/shingles, 0 otherwise; 0.003
Year built	Year construction completed; 1960
ExpEnergy	Annual energy expenditures; 158,830
California	1 if in state of California, 0 otherwise; 0.12

Table A.3. General circulation model climate changes

	Hadley-2100				PCM-2100			
	Temperature		Precipitation		Temperature		Precipitation	
County	**Jan.**	**July**	**Jan.**	**July**	**Jan.**	**July**	**Jan.**	**July**
Alameda	3.97	3.36	74.6%	2.2%	2.01	2.332	-21.1%	-59.7%
Alpine	4.04	4.16	63.8%	-21.4%	1.98	2.76	-17.1%	-32.1%
Amador	4.38	3.91	65.9%	13.0%	2.17	2.57	-18.6%	-24.8%
Butte	4.32	4.30	65.3%	2.6%	2.23	2.73	-16.8%	-55.2%
Calaveras	4.40	3.91	66.1%	14.3%	2.15	2.58	-18.9%	-16.9%
Colusa	4.11	3.95	69.4%	31.1%	2.11	2.50	-20.1%	-45.8%
Contra Costa	3.98	3.40	73.8%	3.6%	2.00	2.37	-21.0%	-59.6%
Del Norte	3.84	3.85	55.3%	6.3%	2.10	2.48	-15.1%	-29.2%
El Dorado	4.39	4.12	65.1%	4.4%	2.16	2.70	-17.7%	-34.0%
Fresno	4.33	3.83	74.3%	-17.1%	2.11	2.61	-16.9%	-28.6%
Glenn	4.11	4.15	68.4%	-4.1%	2.17	2.62	-19.5%	-29.0%
Humboldt	3.84	3.84	64.4%	0.3%	2.09	2.51	-17.6%	-30.2%
Imperial	4.18	3.63	71.1%	22.0%	2.40	3.08	8.7%	-78.9%
Inyo	4.75	4.28	79.9%	-4.7%	2.24	3.11	-11.9%	-44.8%
Kern	4.29	3.85	87.2%	14.7%	2.27	2.76	-12.8%	-66.0%
Kings	4.28	3.72	83.0%	0.0%	2.17	2.54	-17.4%	-70.4%
Lake	3.98	3.84	70.7%	11.7%	2.06	2.49	-20.3%	-46.0%
Lassen	4.17	4.60	59.8%	-12.6%	2.13	2.97	-13.4%	-79.2%
Los Angeles	4.14	3.69	92.7%	9.8%	2.29	2.75	-8.7%	-69.9%
Madera	4.38	3.86	69.9%	-24.3%	2.10	2.60	-18.0%	-22.4%
Marin	3.92	3.46	74.5%	69.4%	2.02	2.40	-21.2%	-80.1%
Mariposa	4.43	3.92	67.4%	-20.9%	2.10	2.63	-18.4%	-17.3%
Mendocino	3.87	3.78	70.9%	16.6%	2.08	2.51	-19.8%	-44.2%
Merced	4.19	3.55	75.1%	2.5%	2.04	2.41	-20.1%	-51.5%
Modoc	4.19	4.60	52.5%	5.4%	2.21	2.96	-11.7%	-63.3%
Mono	4.32	4.26	64.6%	-21.4%	2.03	2.90	-16.6%	-36.5%
Monterey	4.06	3.37	84.4%	3.4%	2.03	2.22	-19.9%	-72.7%
Napa	4.05	3.69	71.5%	55.1%	2.06	2.45	-20.8%	-77.4%
Nevada	4.35	4.26	65.0%	15.9%	2.20	2.76	-16.6%	-49.5%
Orange	4.15	3.46	87.6%	0.0%	2.30	2.71	-5.3%	-58.0%
Placer	4.31	4.23	65.0%	4.8%	2.11	2.73	-17.1%	-42.7%
Plumas	4.23	4.52	63.7%	-16.8%	2.10	2.89	-15.2%	-65.7%
Riverside	4.19	3.73	81.0%	11.2%	2.33	3.06	0.0%	-55.2%
Sacramento	4.26	3.82	68.3%	76.6%	2.11	2.50	-19.8%	-47.8%
San Benito	4.11	3.41	81.0%	11.4%	2.05	2.29	-20.2%	-68.5%

Table A.3. General circulation model climate changes (cont.)

	Hadley-2100				PCM-2100			
	Temperature		Precipitation		Temperature		Precipitation	
County	Jan.	July	Jan.	July	Jan.	July	Jan.	July
San Bernardino	4.42	4.08	82.7%	-14.5%	2.31	3.20	-3.3%	-54.3%
San Diego	4.07	3.38	77.9%	34.2%	2.32	2.77	1.8%	-58.2%
San Francisco	3.92	3.25	75.4%	0.0%	1.92	2.35	-21.4%	-75.0%
San Joaquin	4.18	3.61	70.3%	16.4%	2.04	2.43	-20.4%	-48.4%
San Luis Obispo	4.13	3.51	89.4%	-15.8%	2.15	2.34	-17.5%	-79.4%
San Mateo	3.88	3.19	78.8%	3.8%	2.03	2.27	-21.3%	-58.2%
Santa Barbara	4.12	3.51	98.1%	-0.5%	2.19	2.35	-14.9%	-65.6%
Santa Clara	3.98	3.28	78.1%	18.5%	2.00	2.26	-21.0%	-55.2%
Santa Cruz	3.93	3.21	80.0%	17.2%	1.95	2.19	-21.1%	-40.0%
Shasta	4.22	4.39	60.6%	-6.0%	2.25	2.79	-15.6%	-46.5%
Sierra	4.32	4.44	64.0%	-11.2%	2.16	2.88	-15.7%	-55.1%
Siskiyou	3.85	4.23	55.5%	-0.5%	2.03	2.70	-14.9%	-34.9%
Solano	4.06	3.63	71.2%	17.8%	2.03	2.45	-20.8%	-59.0%
Sonoma	3.92	3.59	73.5%	69.4%	2.04	2.44	-20.9%	-61.3%
Stanislaus	4.18	3.55	72.7%	-6.7%	2.04	2.41	-20.4%	-39.0%
Sutter	4.26	4.02	68.1%	143.7%	2.15	2.55	-19.4%	-79.3%
Tehama	4.16	4.29	65.4%	-13.9%	2.20	2.72	-17.5%	-38.4%
Trinity	3.96	4.08	62.8%	-10.4%	2.11	2.63	-17.6%	-20.6%
Tulare	4.36	3.98	78.7%	-4.5%	2.16	2.80	-14.5%	-44.9%
Tuolumne	4.33	3.99	65.4%	-18.6%	2.07	2.66	-18.3%	-19.1%
Ventura	4.12	3.57	94.2%	-7.1%	2.25	2.55	-11.9%	-76.9%
Yolo	4.15	3.80	69.6%	58.1%	2.10	2.49	-20.5%	-60.8%
Yuba	4.37	4.23	66.2%	73.7%	2.18	2.72	-17.6%	-61.7%